Open access • Journal Article • DOI:10.1111/GCB.15067

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Published on: 01 May 2020 - Global Change Biology (Glob Chang Biol)

Topics: Renewable energy, Wilderness, Energy planning and Wilderness area

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Article type : Primary Research Articles

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For *Global Change Biology* as a Primary Research Article

Renewable energy development threatens many globally important biodiversity areas

Running head Renewable energy threatens biodiversity areas

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Abstract

Transitioning from fossil fuels to renewable energy is fundamental for halting anthropogenic climate change. However, renewable energy facilities can be land-use intensive and impact conservation areas, and little attention has been given to whether the aggregated effect of energy transitions poses a substantial threat to global biodiversity. Here, we assess the extent of current and likely future renewable energy infrastructure associated with onshore wind, hydropower and solar photovoltaic generation, within three important conservation areas: protected areas, Key Biodiversity Areas and Earth's remaining wilderness. We identified 2,206 fully operational renewable energy facilities within the boundaries of these conservation areas, with another 922 facilities under development. Combined, these facilities span and are degrading 886 protected areas, 749 Key Biodiversity Areas, and 40 distinct wilderness areas. Two trends are particularly concerning. First, while the majority of historical overlap occurs in Western Europe, the renewable electricity facilities under development increasingly overlap with conservation areas in South East Asia, a globally important region for biodiversity. Second, this next wave of renewable energy infrastructure represents a ~30% increase in the number of protected areas and Key Biodiversity Areas impacted and could increase the number of compromised wilderness areas by ~60%. If the

world continues to rapidly transition towards renewable energy these areas will face increasing pressure to allow infrastructure expansion. Coordinated planning of renewable energy expansion and biodiversity conservation is essential to avoid conflicts that compromise their respective objectives.

Keywords: Renewable Energy, Conservation Planning, Energy Planning, Sustainable Development, Sustainability, Climate Change, Climate Emergency.

Introduction

The Anthropocene provides numerous global challenges for biodiversity conservation but two dominate: human-driven climate change and widespread habitat loss (Barnosky *et al.*, 2011; IPCC, 2014b; Lewis & Maslin, 2015; Scheffers *et al.*, 2016; Scholes *et al.*, 2018). Nations have pledged to address these challenges in international agreements, including those under the United Nations Framework Convention on Climate Change (UNFCCC) and Convention on Biological Diversity (CBD). To conserve Earth's remaining biodiversity, efforts must focus on both averting immediate species extinctions by protecting critical habitats of imperilled species, and proactively securing the remaining intact ecosystems globally (Watson & Venter, 2017). To halt anthropogenic climate change, a prompt shift towards renewable energy is critical (Audoly *et al.*, 2018; IPCC, 2014a; Pfeiffer *et al.*, 2016).

Both conservation action and renewable energy production can require large areas of land, with the latter requiring up to ten times more land area than fossil fuel thermal facilities to produce equivalent amounts of energy (Lee & David, 2018; Trainor *et al.*, 2016; UNCCD, 2018). Since energy infrastructure development can damage the environment through habitat conversion and degradation (via construction of roads and infrastructure) and increased species mortality (via collisions), the introduction of renewable energy generators into conservation areas could undermine biodiversity conservation efforts (Allison *et al.*, 2014; Bellard *et al.*, 2012; Di Marco *et al.*, 2015; Santangeli *et al.*, 2016; Trainor *et al.*, 2016; Tucker *et al.*, 2018; UNCCD, 2018).

Global efforts to avert the extinction crisis have focused on the establishment of Protected Areas (PAs), which are essential for securing populations of many threatened species (Watson *et al.*, 2014). When managed effectively, PAs maintain higher species richness and abundance than unprotected sites exposed to human pressure (Gray *et al.*, 2016).

The global PA estate extends across ~ 15% of Earth's terrestrial surface, and under the International Union for Conservation of Nature's (IUCNs) definition, a successful protected area "conserves the composition, structure, function and evolutionary potential of biodiversity" (Dudley, 2008; IUCN and UNEP-WCMC, 2018). Within and beyond the protected area estate, conservation scientists have been mapping Key Biodiversity Areas (KBAs) and globally significant wilderness areas as they are important conservation areas that need to be secured if the biodiversity crisis is to be averted (IUCN, 2016; Watson *et al.*, 2016). KBAs are essential sites to avoid species' immediate extinctions and are often the refugia of rare or endangered species (Newbold *et al.*, 2015; Yackulic *et al.*, 2011). Earth's remaining wilderness contains the most intact ecosystems globally, which left to function naturally support an exceptional range of environmental values compared to more degraded or human-modified landscapes, and are buffers against the impacts of climate change (Allan *et al.*, 2017a; Watson *et al.*, 2018a). Both KBAs and wilderness areas are key strongholds for imperilled biodiversity, so securing them from land-use change is increasingly accepted as crucial for averting the biodiversity extinction crisis (Mackey *et al.*, 2013; Watson *et al.*, 2018b).

A transformation of the global energy sector is already underway. Renewable energy sources now contribute ~1/4 of the world's growing electricity production, with the number of renewable energy facilities tripling since 2003 (Obama, 2017; OECD/IEA, 2018). In International Energy Agency scenarios (IEA, 2017b) consistent with the Paris Climate Agreement and the United Nations Development Goals (UN, 2015; UNFCCC, 2015), hydropower, wind and solar photovoltaic generation accounts for the majority of renewable power generation.

Although crucial for mitigating climate change, renewable energy infrastructure development can negatively affect biodiversity. For example, it has been found that hydropower dams negatively affect local, downstream and upstream biodiversity, by modifying sediments, nutrients and altering water flows (Anderson *et al.*, 2015; Lees *et al.*, 2016; Young *et al.*, 2011). Wind power turbines negatively affect birds and bats, which collide with the turbine blades, with ramifications for species in other trophic levels too, and they also modify the natural airflow of local climates (Arnett & Baerwald, 2013; Saidur *et al.*, 2011; Schuster *et al.*, 2015; Thaker *et al.*, 2018; Zhou *et al.*, 2012). Solar photovoltaic energy requires large areas of land for solar panels, which, if poorly planned, leads to habitat conversion (Hernandez *et al.*, 2015; Lovich & Ennen, 2011; Moore *et al.*, 2017). Moreover, the secondary and supporting infrastructure of all these facilities includes transmission lines and roads which can facilitate threats such as hunting, indirect habitat loss, fragmentation and invasive species dispersal, resulting in impacts that extend far beyond their immediate physical footprint (Hovick *et al.*, 2014; Ibisch *et al.*, 2016; Laurance & Arrea, 2017; Sonter *et al.*, 2017a).

Despite the strong and often negative feedbacks between biodiversity conservation and renewable energy expansion, policies to promote these two objectives are almost always planned separately (Koppel *et al.*, 2014). By intending to avoid conflicts with local communities and other agricultural or natural resource operations, both objectives may unknowingly target the same sites. Consequently, by co-locating, the production of renewable energy could seriously compromise conservation efforts (Gasparatos *et al.*, 2017; Gibson *et al.*, 2017). Mitigating climate change and averting the current biodiversity crisis will therefore require governments, and other decision-makers, to understand where these goals conflict, which is where renewable energy development and important biodiversity conservation areas overlap. Previous studies have used scenarios to predict conflicts of bioenergy, wind, and solar photovoltaic focused on PAs (Meller *et al.*, 2015; Santangeli *et al.*, 2016). To our knowledge, no global study has assessed the existing and near-term future renewable energy infrastructure relative to a more comprehensive set of important sites for biodiversity conservation.

Here, we analyse spatial congruence between current (operational) and under development large-scale renewable energy facilities that produce electricity (hereafter renewable energy facilities) and the established PA estate, and mapped areas of globally significant wilderness and KBAs. Our study is focused on hydropower, solar photovoltaic and onshore wind power, as they are the mature renewable energy technologies for electricity generation that dominate the renewables sector. We use an industry-standard dataset of renewable energy facilities locations. As such, we provide the first comprehensive global assessment of current and possible future overlaps between renewable energy technologies and important biodiversity conservation areas.

Materials and methods

Defining important conservation areas

We collected spatial data on Protected Areas (PAs), Key Biodiversity Areas (KBAs) and wilderness areas. As discussed, when combined, these three conservation values provide a spatial representation of the primary objectives of biodiversity conservation, which includes; 1) preventing the decline and extinction of species; 2) securing populations of all species in their natural patterns of abundance and distribution; and 3) protecting the places that maintain ecological and evolutionary processes (CBD, 2011; Dinnerstein *et al.*, 2017; Watson & Venter, 2017). PAs are primarily identified and protected by the countries they are situated in, and as such, are nationally recognized as worthy of conservation. KBAs and wilderness areas do not necessarily have formal protection; however, they are widely regarded as critical for biodiversity conservation and are considered priority sites for protected area expansion (Allan *et al.*, 2017a; Butchart *et al.*, 2012; Smith *et al.*, 2019). We hereafter refer to PAs, KBAs and wilderness areas collectively as 'important conservation areas'.

We obtained spatial data on PA boundaries from the July 2018 version of the World Database on Protected Areas (WDPA) (IUCN and UNEP-WCMC, 2018). This is the most comprehensive database available, containing information on all the PAs that countries have reported to the International Union for Conservation of Nature (IUCN), including China, which has since removed national PAs from the database. We excluded PAs < 5km^2 and point data from the analysis to reduce miscalculations due to data resolution, an approach consistent with other recent studies (e.g. Jones *et al.* (2018)). This has a negligible effect on the extent of protected area coverage, as these small protected areas account for only 0.5% of the global land area protected. We eliminated any co-occurrence of PAs by dissolving overlapping polygons, following WDPA best-practice guidelines (https://www.protectedplanet.net/c/calculating-protected-areacoverage). A total of 41,083 PAs across management categories I-VI as defined by the IUCN qualified for the analysis (Dudley, 2008). Results are reported separately for the group of PA categories I to IV, as these completely prohibit any development within their boundaries. Our other group includes PA categories V and VI, which allow development that does not compromise the PAs biodiversity conservation objectives (Dudley, 2008), and those PAs that are not categorised in the source maps.

We obtained spatial data on the boundaries of KBAs from the World Database of Key Biodiversity Areas (BirdLife International, 2018). We did not modify this data, and a total of 18,268 KBAs qualified for the analysis. This covers all the IUCN (2016) KBA categories, including important bird areas, sites prioritised to avoid specific species from going extinct, and other zones identified as crucial for the persistence of threatened biodiversity.

We obtained data on the global extent of Wilderness Areas from Allan *et al.* (2017b). We used the 'Last of the Wild' map which identifies the most ecologically intact places on Earth. To produce the map, Allan *et al.* (2017) identified the 10% (by area) of each of the Earth's Biogeographic Realms (Biomes within Realms, e.g. Boreal forests within the Palearctic or Nearctic realms) with the lowest Human Footprint (Venter *et al.*, 2016). The Human Footprint is a globally standardised map of cumulative human pressure on the natural environment. From this, all contiguous areas > 10,000 km^2 were selected, in Biorealms that didn't have 10 contiguous blocks > 10,000 km^2, the next largest patch was consecutively selected until there were 10 per Biorealm. The final map contains 834 contiguous wilderness areas.

Assessing the current spatial overlap between renewable energy facilities and important conservation areas

We overlapped the locations of important conservation areas with the locations of operational renewable energy facilities to explore potential clashes. To map the 'operational' fleet of renewable electricity facilities, we obtained data on the location and capacity of solar photovoltaic (PV), onshore wind-power and hydropower generators from the GlobalData Power Database (GlobalData, 2018). Our operational facilities dataset only includes facilities classified as 'active' in the source database (Table S2, Supplementary methods). While we exclude historical facilities where operations have ceased, or the infrastructure development has been halted, those exclusions account for only 0.4 % of the total number, and 0.3 % of the total generation capacity of all operational global facilities. This is one of the most complete global collections of electricity generation facility information, which we estimate included ~90% of the world's PV, onshore wind and hydropower capacity in 2017 (Table S3, supplementary methods). We independently validated the accuracy of the energy facility locations in the GlobalData Power database using Google Earth imagery. We inspected 257 randomly selected points across all continents and countries, and found that 239 (94%) were located correctly, aligning with facilities in the images and demonstrating a high degree of accuracy (Table S4, see supplementary methods for more detail).

To explore recent trends associated with the current boom in renewable energy developments, we separately compared the maps of important conservation areas with a map of facilities that we categorise as being currently 'under development'. This group includes facilities classified in GlobalData (2018) as being either 'partially active', 'under construction', 'financed', 'permitting' or 'announced' (Table S2, Supplementary methods).

The former three could be considered as having a high probability of reaching the operating stage, with the 'partially active' classification implying that the facilities are still under construction but already partly operational. While the last two classifications would be considered less likely to proceed, particularly those classed as 'announced', we include them here because they reflect a decision by either business and/or government stakeholders to site a renewable generation facility at a specific location. As such, their inclusion supports analysis focused on where the current renewable generation development activity might pose the greatest risks to important conservation areas.

To focus our analysis on large renewable generation infrastructure, both the operational and under development category datasets were constrained to facilities with a nominal generation capacity above 10MW. Large scale facilities can be developed in isolated areas because of economies of scale and preference for high energy resources, posing a threat to areas that may be free of human pressures (Walston *et al.*, 2016; Winemiller *et al.*, 2016). While local factors might influence what is considered a 'large' facility in any particular region, the 10MW threshold is consistent with examples used across the academic literature (Hoes *et al.*, 2017), the International Renewable Energy Agency (IRENA, 2015) and some national legislation (Congreso Nacional de Chile, 2004). After excluding facilities below 10MW capacity, the dataset represents 93% and 99% of the total capacity for the operational and under development categories respectively, and 29% and 78% (respectively) of the total number of facilities. The difference in coverage across the operational and under development categories illustrates the globally relevant trend underway, which is towards the installation of increasingly larger renewable generation facilities. Overlapping facilities are classified independently for ten contiguous regional boundaries (Table S1, Supplementary Methods) and by country using the TM World borders 3.0 layer based on United Nations ISO3 country coding.

Results

Current renewable energy facilities

Out of 12,658 large scale renewable energy facilities distributed globally, we found that 2,206 (17.4%) currently operate inside important conservation areas (Table 1). Of these facilities, 1,018 overlap with 634 PAs (1.5% of the total number of PAs), of which 122 are classified as strictly managed PAs (IUCN Categories I-IV), where no development activity should occur (Table 2, Figure 1). These 122 strictly managed PAs contain 169 renewable energy facilities (Table 2). We identified 42 facilities overlapping with 25 contiguous wilderness areas (2.7% of total wilderness blocks), and 1,147 facilities within 583 KBAs (3.2% of the total number of KBAs). Wind power overlaps with the largest number of important conservation areas (n = 543 PAs, KBAs and wilderness areas combined).

Table 1. *Overlap between operational renewable energy facilities and protected areas (PAs), Key Biodiversity Areas (KBAs) and wilderness areas.*

Important conservation areas	**Criteria**	**Wind power**	**Photovoltaic**	**Hydropower**	**Total**
Protected areas	Number of assets affected (%)	289 (0.7)	99 (0.2)	246 (0.6)	634 (1.5)
	Area of assets affected - Km^2 (%)	350,164 (1.2)	129,075 (0.4)	555,741 (1.9)	1,034,980 (3.5)
	Number of facilities (%)	477 (7)	146 (5)	394 (12)	1,018 (8)
	Total capacity - MW (%)	13,767 (5)	3,338 (3)	73,124 (11)	90,229 (8)
Key Biodiversity Areas	Number of assets affected (%)	249 (1.4)	100 (0.6)	269 (1.5)	583 (3.2)
	Area of assets affected - Km^2 (%)	186,745 (1.7)	233,834 (2.1)	234,982 (2.1)	599,609 (5.4)
	Number of facilities (%)	559 (9)	201 (7)	387 (12)	1,147 (9)
	Total capacity - MW (%)	20,305 (7)	9,011 (9)	77,293 (11)	106,609 (10)
Wilderness	Number of assets affected (%)	5 (0.6)	4 (0.4)	16 (1.8)	25 (2.8)
	Area of assets affected - Km^2 (%)	140,728 (0.5)	600,800 (2)	454,270 (1.5)	1,195,798 (3.9)
	Number of facilities (%)	11 (0.2)	5 (0.2)	26 (1)	42 (0.3)
	Total capacity – MW (%)	1,217 (0.4)	73 (0.1)	2,826 (0.4)	4,116 (0.4)

Figure 1. Overlap between operational renewable energy facilities and important conservation areas (shown in green). Panels show operational renewable energy facilities within (a) Key Biodiversity Areas, (b) wilderness areas, and (c) protected areas. Circles represent renewable energy facilities, with colours representing the different technologies, and size representing the capacity of the facility.

__Table 2.__ Overlap between operational and under development renewable energy facilities (solar, wind and hydro) and strict or non-strict protected areas (PAs).

Important conservation areas	Criteria	Wind		Photovoltaic		Hydropower		All energy technologies		
		Operational	**Under development**	**Operational**	**Under development**	**Operational**	**Under development**	**Operational**	**Under development**	**Combined (Op + U.d.)**
Strict PAs	Number of assets affected (%)	43 (0.4)	19 (0.2)	19 (0.2)	24 (0.2)	62 (0.6)	23 (0.2)	122 (1.2)	61 (0.6)	175 (1.8)
	Number of facilities (%)	59 (12)	28 (22)	37 (25)	36 (26)	73 (19)	36 (22)	169 (17)	100 (23)	269 (19)
Non-Strict PAs	Number of assets affected (%)	298 (1.6)	110 (0.6)	88 (0.5)	76 (0.4)	279 (1.5)	32 (0.2)	635 (3.4)	205 (1.1)	789 (4.3)
	Number of facilities (%)	418 (88)	102 (78)	109 (75)	103 (74)	322 (82)	127 (78)	849 (83)	332 (77)	1181 (81)

Overlaps occur across all regions, however there is substantial heterogeneity in their spatial distribution (Figure 1). Western Europe dominates the overall number of overlaps, and the Middle East and Africa have the largest proportion of renewable energy facilities inside conservation areas (Figure 2). The distribution of overlaps varies by the type of conservation area - greater overlaps can be found for PAs and KBAs in Europe, and Japan; whereas most of the overlaps with wilderness areas are in China and North America (Figure 1). The spatial distribution also varies across the different generation technologies. The overlaps between solar and wind energy facilities, and conservation areas, are found mostly in Europe, and Northeast Asia; while the overlaps with hydropower are more homogenously distributed worldwide. The country with the most overlaps between current facilities and important conservation areas is Germany (n = 258), mostly within non-strict PAs (n = 138) and KBAs (n = 119). Other notable examples include Spain, with 252 overlaps, including 188 with KBAs, and China with 142 facilities within KBAs, most of which are hydropower plants (n = 63) (Table S5, Supplementary materials). In Spain and Germany wind power facilities overlap with 166 KBAs and 88 KBAs respectively.

Figure 2. The number (a) and proportion (b) of operational (red) and under development (orange) renewable energy facilities within important conservation areas (protected areas, Key biodiversity areas and wilderness areas) by energy region.

Renewable energy facilities under development

We found 922 renewable energy facilities under development in 525 important conservation areas (Table 3, Figure 3), which represents a potential increase of 42% over the number of operational facilities, within the next ~8 years. Some of these renewable energy facilities under development (556) overlap with an additional 166 KBAs, 15 wilderness areas and 187 PAs (of which 61 are strict PAs) presently without energy facilities. Almost one-quarter of all facilities under development that overlap with important conservation areas are sited within strict PAs (n = 100). Combined, these under development facilities would increase the number of impacted conservation areas by 29%. If we assume that all facilities under development are to be operational by 2025, 749 KBAs (8.5%), 40 wilderness blocks (5.7%), and 886 PAs (6%) (of which 175 are strict PAs) will contain 3128 large-scale renewable energy facilities (Table 3 and Figure S1, Supplementary materials).

The distribution of renewable energy facilities under development inside important conservation areas differs from that of operational facilities (Figure 2 and 3). Most facilities under development overlapping with conservation areas are in India and Southeast Asia instead of Western Europe. Overlaps, in this case, are distributed more homogeneously between regions, with clusters around China, India and Southeast Asia, especially for PAs and KBAs. Overlapping facilities currently under development are also more homogeneously distributed across the globe respective to technology types, since wind energy and solar photovoltaic are spreading to new regions. Nepal has the most overlaps between facilities under development and important conservation areas (n = 110). This is predominantly driven by hydro, with 102 facilities within PAs (six within strict PAs) and eight within KBAs. The trend is similar for India, which has 74 hydro facilities under development in important conservation areas, including 27 within PAs (16 within strict PAs) and 21 within KBAs (Table S5, Supplementary Materials).

Most of the facilities under development that overlap with important conservation areas are located within PAs (432 facilities inside 252 PAs); however, the proportion of distinct wilderness areas that contain facilities under development is also higher (n = 17, 1.9%). The number of photovoltaic and wind energy facilities inside important conservation areas appears to be growing rapidly, with 177 and 234 facilities under development, representing increases of 80% and 30% over historic numbers respectively.

Figure 3. Overlap between renewable energy facilities under development and important conservation areas (shown in green). Panels show renewable energy facilities under development within (a) Key Biodiversity Areas, (b) wilderness areas, and (c) protected areas. Dots represent renewable energy facilities, with colours representing the different technologies, and size representing the capacity of the facility.

__Table 3.__ Overlap of renewable energy facilities under development with important conservation areas (Protected Areas, Key Biodiversity Areas and wilderness areas).

Conservation areas	Criteria	Wind power	Photovoltaic	Hydropower	Total renewable energy: Under Development	Total renewable energy: New*	Total renewable energy: Combined**
Protected areas	Number of assets affected (%)	116 (0.3)	91 (0.2)	45 (0.1)	252 (0.6)	187 (0.5)	886 (2.2)
	Area of asset affected - Km^2 (%)	307,307 (1)	269,248 (0.9)	162,639 (0.5)	734,194 (2.5)	406,835 (1.4)	1,774,174 (6)
	Number of facilities (%)	139 (5)	130 (4)	163 (18)	432 (7)	238	1,450 (8)
	Total capacity - MW (%)	15,700 (6)	13,669 (5)	34,154 (11)	63,523 (8)	25,809	153,752 (8)
Key Biodiversity Areas	Number of affected features (%)	110 (0.6)	81 (0.4)	65 (0.4)	247 (1.4)	166 (0.9)	749 (4.1)
	Area of affected features - Km^2 (%)	173,263 (1.6)	172,809 (1.5)	165,074 (1.5)	478,793 (4.3)	352,085 (3.2)	951,874 (8.5)
	Number of facilities (%)	162 (6)	152 (5)	155 (17)	469 (7)	299	1,616 (8)
	Total capacity - MW (%)	12,532 (5)	17,323 (7)	40,165 (13)	70,020 (8)	44,433	176,629 (9)
Wilderness	Number of affected features (%)	8 (0.9)	5 (0.5)	4 (0.4)	17 (1.9)	15 (1.7)	40 (4.4)
	Area of affected features - Km^2 (%)	308,289 (1)	665,672 (2.2)	73,577 (0.2)	1.047,538 (3.5)	527,164 (1.7)	1,722,962 (5.7)
	Number of facilities (%)	8 (0.3)	5 (0.2)	8 (1)	21 (0.3)	19	63 (0.3)
	Total capacity – MW (%)	7,268 (3)	943 (0.4)	1,414 (0.5)	9,625 (1.1)	8,112	13,741 (1)

*New includes facilities that are being developed in important conservation areas which do not currently have any operational renewable energy facilities within their boundaries. **Combined is the sum of the facilities that are currently operational and under development.

Discussion

Effective conservation efforts and a transition to a renewable energy future are both essential to prevent species extinctions and avoid catastrophic climate change (Cardinale *et al.*, 2012; Griscom *et al.*, 2017; IPCC, 2014a; Thomas *et al.*, 2004). Nevertheless, their planning in isolation will reduce the effectiveness and momentum of both efforts. Our results show that renewable energy development has already encroached on many of the world's most important places for conserving biodiversity, with 1,277 facilities already operational within PAs, KBAs and wilderness areas (Figure S2, Supplementary Materials). Furthermore, the number of active energy facilities inside important conservation areas could increase by ~42% by 2028, suggesting conflicts will likely intensify in the near future. Many important conservation areas contain renewable energy resources that could potentially be exploited to produce electricity in the future, and will likely face increased pressure from developments as the demand for renewable energy inevitably grows (Santangeli *et al.,* 2016). This is especially worrying, when assessments show the growth required to achieve the UN climate targets by 2060 (Bauer *et al.,* 2017; IEA 2017b) would be an order of magnitude greater than the installed capacity included in our 'operational' and 'under development' datasets.

Most of the overlap between current renewable energy facilities and important conservation areas is concentrated in developed regions, which tend to also have the greatest total number of renewable energy facilities. However, our analysis suggests that many future overlaps will be concentrated in developing regions. Over half (51%) of the overlapping facilities under development are situated in India, South-east Asia, South America or Africa. The technologies driving overlaps differ considerably between regions and countries. For example, hydropower facilities under development are driving large numbers of the potential future overlaps in India and Nepal, impacting protected areas in particular. In China and Kuwait solar photovoltaic plants under development are driving potential future overlaps with important conservation areas, whereas in Costa Rica it is predominantly wind facilities (Table S5, Supplementary Materials). This highlights that each nation needs to have its own specific planning systems in place to deal with future energy generation problems.

Many of the developing regions affected by the new wave of renewables infrastructure are incredibly important for global biodiversity. Given the prevalence of human population and land-use pressures in those countries, the current suite of conservation areas may well be the only remaining places to conserve biodiversity (Hughes, 2017). That means any encroachment by the renewable energy sector will compromise conservation outcomes. Proactive land-use planning that meets best practice mitigation hierarchy standards will be crucial to avoid biodiversity loss from renewable energy infrastructure expansion in these areas (Shum, 2017; Sonter *et al.*, 2018). However, many developing countries lack strong land-use planning policies, making the conservation assets they contain particularly vulnerable to land-use change due to industrial activity (Fritsche *et al.*, 2017). This is demonstrated in Africa and the Middle East where our analyses show that 38% and 33% of respective operational renewable energy facilities are located within important conservation areas. As African countries in particular are pursuing aggressive development agendas, with economic growth almost always superseding environmental safeguards (Lesutis, 2019), the likely consequence is that many other important conservation areas will be impacted in the future.

Multi-objective land-use planning that accounts for biodiversity conservation is still rare in the energy sector, and development decisions are often dependent on local legislation and socio-economic constraints, coupled with the availability and desires of project proponents instead (Poggi *et al.*, 2018; Strantzali & Aravossis, 2016). Most large-scale renewable energy planning projects do not explicitly account for biodiversity conservation objectives. For example, Chile recently underwent a national zoning process to promote large-scale renewable energy development, and the International Renewable Energy Agency is identifying zones for a continent-wide energy corridor across Africa, and both are blind to biodiversity outcomes (IRENA, 2015; Moreno *et al.*, 2015; Wu, 2015). Fortunately, these projects are in their infancy, so there are still opportunities to incorporate biodiversity conservation objectives into the planning process. The conservation community must engage in this type of industrial level strategic planning by providing clearly delineated maps of critical land essential for biodiversity outcomes to developers and governments.

Similarly, the energy industry should actively respect the concern that they may cause harm to areas important to biodiversity, recognising that it is critical to avoid sites that have been formally identified as important conservation areas. However, to move forward without conflict, governments and the energy industry must strengthen Environmental and Social Impact Assessments (ESIAs), and apply a more rigorous mitigation hierarchy to reduce the risk of important conservation areas being developed (Arlidge *et al.*, 2018). Economic subsidies combined with strategic planning can also prioritise new energy developments towards already degraded lands to reduce energy-biodiversity land-use conflicts in the future (Hartmann *et al.*, 2016; Kiesecker *et al.*, 2011; Waite, 2017).

There are also inherent differences among energy technologies in the potential for conflict, and making solar energy the focus for new developments may facilitate the avoidance of important conservation areas. High solar irradiation is widely available in low-biodiversity and degraded lands, and there may be some potential for power to be traded out of such regions, into countries with less potential for low-conservation impact energy generation (Antweiler, 2016). Having fewer large energy facilities towards many smaller dispersed facilities could reduce the land requirements of energy development (Moroni *et al.*, 2016). In the case of solar, this means existing infrastructure can be harnessed (e.g. putting solar panels on house roofs) instead of building ground-mounted facilities.

Our analysis suggests that strict protected areas (IUCN categories I to IV) provide more effective protection against renewable energy development than less strict (categories V and VI) and non-categorised protected areas. This finding is consistent with analyses showing that the strict protection categories perform better at limiting the spread of other human pressures (such as agriculture, grazing and urbanisation) within their boundaries (Jones 2018). Therefore, the expansion of strict protected areas, and upgrading the management of less strict PAs could be central to global efforts to safeguard biodiversity, when it comes to abating risk from large-scale industry. However, it is no silver bullet, as we found large numbers of renewable energy facilities under development within strict PAs, and these strongly predict subsequent PA downgrading, downsizing or degazettement, which leads to worse biodiversity outcomes (Mascia 2011, Symes 2018). Interestingly, solar-photovoltaic facilities are more likely to be found within stricter PAs than the other energy technologies. The reason for this is unclear, although it would be concerning if the social and climate mitigation appeal of solar energy was motivating or enabling planners to bypass the protection mechanisms afforded by a PA classification (Dudley 2008). Our research shows that there is an important assessment to be done exploring the relationship between total energy supply and renewable energy production, and how this affects patterns of overlaps by country for PAs, which is worth exploring in future analyses.

It is important to recognise that the analysis provided here could underestimate the extent of current and future impact of renewable energy generation on natural systems for several reasons. Firstly, because we excluded smaller energy facilities (<10 MW) and the transmission lines and roads required to connect energy generation sites to the grid. The impacts of this associated infrastructure can be substantial, affecting large areas of land and fragmenting habitats (Bevanger, 1998; Cunningham *et al.*, 2016; Söderman, 2006). Secondly, we excluded the remote regions of Antarctica and Greenland, whose unique conservation values could be threatened if their lack of land use conflicts made them attractive for large scale renewable energy development (Lee, 2017). Finally, there are also concerns related to the potential for renewable energy facilities to compromise ecosystem services, such as flood mitigation or carbon storage (Sonter *et al.,* 2017b). For example, if renewable energy developments led to the conversion of carbon-rich habitat (e.g. tropical forests), then this would potentially be a lose-lose outcome for both biodiversity and climate stabilisation objectives. Exploring the extent of carbon and biodiversity impacts from renewable energy facilities would be an interesting avenue for future work, extending this analysis beyond its sole focus on biodiversity conservation areas and priorities.

Conclusion

We have determined the extent of current, and potential future overlap of renewable energy facilities and important conservation areas, showing that overlaps are numerous, and are potentially compromising the goals of biodiversity conservation. Our results also show that the spatial distribution of overlaps is moving from developed regions towards more biodiverse developing regions such as Southeast Asia and sub-Saharan Africa, where the consequences for global biodiversity conservation will be more intense. Strategic planning that simultaneously integrates conservation objectives with the needs of the transitioning energy sector, setting clear limits on development within important conservation areas is urgently needed. If nations pursue a singular focus on decarbonisation through renewable energy expansion, they risk undermining the global mission to avert the biodiversity crisis which they have committed to via the United Nation's Sustainable Development goals.

Acknowledgements

We thank the authors of the global renewable energy resource maps for supplying additional data, answering our queries and providing valuable advice. We are deeply grateful to Estelle Roux, Christopher O'Bryan, Milton Andrade, Brooke Williams, Paul Dargusch, and Jeremy Simmonds for valuable comments on earlier drafts of the manuscript, and to Paula Becerra for help designing figures.

Data sharing and accessibility

Raw data on important conservation areas is publicly available in the respective sites of each organisation (Allan et al., 2017b; BirdLife Internationa,l 2018; IUCN and UNEP-WCMC, 2018). Data for renewable energy facilities can be purchased from GlobalData, 2018.

References

Allan JR, Kormos C, Jaeger T *et al.* (2017a) Gaps and opportunities for the World Heritage Convention to contribute to global wilderness conservation. *Conservation Biology,* **32**(1), 116-126. doi:10.1111/cobi.12976

Allan JR, Venter O, Watson JEM (2017b) Temporally inter-comparable maps of terrestrial wilderness and the Last of the Wild. *Scientific Data,* **4**, 170187. doi:10.1038/sdata.2017.187

Allison TD, Root TL, Frumhoff PC (2014) Thinking globally and siting locally – renewable energy and biodiversity in a rapidly warming world. *Climatic Change,* **126**(1-2), 1-6. doi:10.1007/s10584-014-1127-y

Anderson D, Moggridge H, Warren P, Shucksmith J (2015) The impacts of 'run-of-river' hydropower on the physical and ecological condition of rivers. *Water and Environment Journal,* **29**(2), 268-276.

Antweiler W (2016) Cross-border trade in electricity. *Journal of International Economics,* **101**, 42-51. doi:10.1016/j.jinteco.2016.03.007

Arlidge WNS, Bull JW, Addison PFE *et al.* (2018) A Global Mitigation Hierarchy for Nature Conservation. *BioScience,* **68**(5), 336-347. doi:10.1093/biosci/biy029

Arnett EB, Baerwald EF (2013) Impacts of wind energy development on bats: implications for conservation. *Bat evolution, ecology, and conservation* (pp. 435-456): Springer.

Audoly R, Vogt-Schilb A, Guivarch C, Pfeiffer A (2018) Pathways toward zero-carbon electricity required for climate stabilization. *Applied Energy,* **225**, 884-901.

Barnosky AD, Matzke N, Tomiya S *et al.* (2011) Has the Earth's sixth mass extinction already arrived? *Nature,* **471**, 51. doi:10.1038/nature09678

Bauer N, Calvin K, Emmerling J *et al.* (2017) Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives. *Global Environmental Change,* **42**, 316-330. doi:10.1016/j.gloenvcha.2016.07.006

Bellard C, Bertelsmeier C, Leadley P, Thuiller W, Courchamp F (2012) Impacts of climate change on the future of biodiversity. *Ecology Letters,* **15**(4), 365-377. doi:10.1111/j.1461-0248.2011.01736.x

Bevanger K (1998) Biological and conservation aspects of bird mortality caused by electricity power lines: a review. *Biological Conservation,* **86**(1), 67-76.

BirdLife International (2018) *World Database of Key Biodiversity Areas*. Retrieved from: http://www.keybiodiversityareas.org/home.

Butchard SHM, Scharlemann JPW, Evans MI *et al.* (2012) Protecting Important Sites for Biodiversity Contributes to Meeting Global Conservation Targets. *PLoS ONE, 7*(3), e32529. doi:10.1371/journal.pone.0032529

Cardinale BJ, Duffy JE, Gonzalez A *et al.*(2012) Biodiversity loss and its impact on humanity. *Nature,* **486**, 59. doi:10.1038/nature11148

CBD (2011) Conference of the parties decision X/2 Strategic Plan for Biodiversity 2011 - 2020.

Congreso de Chile (2004) Ley 19.940: Regulación sistemas de transporte de Energía Eléctrica.

Cunningham S, Madden C, Barnard P, Amar A (2016) Electric crows: powerlines, climate change and the emergence of a native invader. *Diversity and Distributions, **22***(1), 17-29.

Di Marco M, Butchart SHM, Visconti P, Buchanan GM, Ficetola GF, Rondinini C (2015) Synergies and trade-offs in achieving global biodiversity targets. *Conservation Biology, **30***(1), 189-195. doi:10.1111/cobi.12559

Dinerstein E, Olson D, Joshi A *et al.* (2017) An Ecoregion-Based Approach to Protecting Half the Terrestrial Realm. Bioscience, **67**(6), 534–545. doi:10.1093/biosci/bix014

Dudley N (2008) *Guidelines for applying protected area management categories*: IUCN.

Fritsche UR, Berndes G, Cowie AL *et al.* (2017) *Energy and Land use*. In: I. Jhonson, S. Alexander & N. Dudley (Eds.), UNCCD Global Land Outlook. Bonn, Germany.

Gasparatos A, Doll CNH, Esteban M, Ahmed A, Olang TA (2017) Renewable energy and biodiversity: Implications for transitioning to a Green Economy. *Renewable and Sustainable Energy Reviews, **70***, 161-184. doi:10.1016/j.rser.2016.08.030

Gibson L, Wilman EN, Laurance WF (2017) How Green is 'Green' Energy? *Trends in Ecology and Evolution, **32***(12), 922-935. doi:10.1016/j.tree.2017.09.007

GlobalData (2018) Power Fundamentals, Power Plants. Retrieved 22/07/2018. Retrieved from: https://power.globaldata.com

Gray CL, Hill SL, Newbold T *et al.* (2016) Local biodiversity is higher inside than outside terrestrial protected areas worldwide. *Nature. 7*, 12306.
Griscom BW, Adams J, Ellis PW *et al.* (2017) Natural climate solutions. *Proceedings National Academy of Sciences, **114***(44), 11645-11650. doi:10.1073/pnas.1710465114
Hartmann HM, Grippo MA, Heath GA *et al.* (2016) Understanding emerging impacts and requirements related to utility-scale solar development. *US Department of energy, Office of Scientific and Technical Information.*
Hernandez RR, Hoffacker MK, Murphy-Mariscal ML, Wu GC, Allen MF (2015) Solar energy development impacts on land cover change and protected areas. *Proceedings National Academy of Sciences, **112***(44), 13579-13584. doi:10.1073/pnas.1517656112
Hovick TJ, Elmore RD, Dahlgren DK, Fuhlendorf SD, Engle DM (2014) Evidence of negative effects of anthropogenic structures on wildlife: A review of grouse survival and behaviour. *Journal of Applied Ecology, **51***(6), 1680-1689. doi:10.1111/1365-2664.12331
Hughes, A. C. (2017). Understanding the drivers of Southeast Asian biodiversity Loss. *Ecosphere*, **8**(1), e01624.
Ibisch PL, Hoffmann MT, Kreft S *et al.* (2016) A global map of roadless areas and their conservation status. *Science, **354***(6318), 1423-1427. doi:10.1126/science.aaf7166
IEA (2015a) *Technology Roadmap, Solar Photovoltaic Energy*. International Energy Agency. Retrieved from https://www.oecd-ilibrary.org/content/publication
IEA (2015b) *Technology Roadmap, Wind Energy*. International Energy Agency. Retrieved from https://www.oecd-ilibrary.org/content/publication
IEA (2017a) *Energy Technology Perspectives 2017, Catalysing Energy Technology Transformations*: International Energy Agency. Retrieved from: https://www.oecd-ilibrary.org/content/publication
IEA (2017b) *World Energy Outlook*. International Energy Agency. Washington, D.C. Retrieved from: https://www.oecd-ilibrary.org/content/publication
IPCC (2014a) *Climate Change 2014 – Impacts, Adaptation and Vulnerability: Part A: Global and Sectoral Aspects: Working Group II Contribution to the IPCC Fifth Assessment Report: Volume 1: Global and Sectoral Aspects* (Vol. 1). Cambridge: Cambridge University Press.
IPCC (2014b) *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate*

Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. Geneva, Switzerland.
IRENA (2015) *Renewable Energy Zones for the Africa clean energy corridor*. Retrieved from https://www.irena.org/publications/
IUCN (2016) *A Global Standard for the Identification of Key Biodiversity Areas*. Gland, Switzerland and Cambridge, UK.
IUCN and UNEP-WCMC (2018) *The World Database on Protected Areas (WDPA)*. Retrieved 12/03/2018. Retrieved from: www.protectedplanet.net
Jones KR, Venter O, Fuller RA, Allan JR, Maxwell SL, Negret PJ, Watson JEM (2018) One-third of global protected land is under intense human pressure. *Science, **360***(6390), 788-791. doi:10.1126/science.aap9565
Kiesecker JM, Evans JS, Fargione J *et al.* (2011) Win-win for wind and wildlife: a vision to facilitate sustainable development. *PLOS ONE, **6***(4), e17566. doi:10.1371/journal.pone.0017566
Koppel J, Dahmen M, Helfrich J, Schuster E, Bulling L (2014) Cautious but committed: moving toward adaptive planning and operation strategies for renewable energy's wildlife implications. *Environmental Management, **54***(4), 744-755. doi:10.1007/s00267-014-0333-8
Laurance WF, Arrea IB (2017) Roads to riches or ruin? *Science, **358***(6362), 442-444. doi:10.1126/science.aao0312
Lee JR, Raymond B, Bracegirdle TJ, Chades I, Fuller RA, Shaw JD, Terauds A (2017) Climate change drives expansion of Antarctic ice-free habitat. *Nature*, **547**(7661), 49. doi:10.1038/nature22996
Lee MM, David WK (2018) Observation-based solar and wind power capacity factors and power densities. *Environmental Research Letters, **13***(10), 104008.
Lees AC, Peres CA, Fearnside PM, Schneider M, Zuanon JAS (2016) Hydropower and the future of Amazonian biodiversity. *Biodiversity and Conservation, **25***(3), 451-466. doi:10.1007/s10531-016-1072-3
Lesutis G. (2019) How to understand a development corridor? The case of Lamu Port–South Sudan–Ethiopia-Transport corridor in Kenya. *Area*. **00**, 1– 9. doi:10.1111/area.12601
Lewis SL, Maslin MA (2015) Defining the Anthropocene. *Nature, **519***, 171. doi:10.1038/nature14258

Lovich JE, Ennen JR (2011) Wildlife Conservation and Solar Energy Development in the Desert Southwest, United States. *BioScience, **61***(12), 982-992. doi:10.1525/bio.2011.61.12.8

Mackey B, Prentice IC, Steffen W, House JI, Lindenmayer D, Keith H, Berry S (2013) Untangling the confusion around land carbon science and climate change mitigation policy. *Nature Climate Change, **3***, 552. doi:10.1038/nclimate1804

Mascia MB, Pailler S (2011) Protected area downgrading, downsizing, and degazettement (PADDD) and its conservation implications. *Conservation letters*, **4**(1), 9-20. doi: 10.1111/j.1755-263X.2010.00147.x

Meller L, Thuiller W, Pironon S, Barbet-Massin M, Hof A, Cabeza M (2015) Balance between climate change mitigation benefits and land use impacts of bioenergy: conservation implications for European birds. *Global Change Biology Bioenergy, **7***(4), 741-751. doi:10.1111/gcbb.12178

Moore-O'Leary KA, Hernandez RR *et al.* (2017) Sustainability of utility-scale solar energy - critical ecological concepts. *Frontiers in Ecology and the Environment, **15***(7), 385-394. doi:10.1002/fee.1517

Moreno R, Pereira E, Gonzalez F (2015) *Informe Final: Zonificación del Sistema Eléctrico Nacional Chileno para Optimizar su Despacho Económico y Seguro*. Coordinador de Despacho Economico de Carga (CDEC). Santiago, Chile.

Moroni S, Antoniucci V, Bisello A (2016) Energy sprawl, land taking and distributed generation: towards a multi-layered density. *Energy Policy, **98***, 266-273. doi:10.1016/j.enpol.2016.08.040

Newbold T, Hudson LN, Hill SL e*t al.* (2015) Global effects of land use on local terrestrial biodiversity. *Nature, **520***(7545), 45-50. doi:10.1038/nature14324

Obama B (2017) The irreversible momentum of clean energy. *Science, **355***(6321), 126-129.

OECD/IEA (2018) World Energy Balances 2018. Retrieved from: https://www.iea.org/statistics/

Pfeiffer A, Millar R, Hepburn C, Beinhocker E (2016) The ‘2°C capital stock’ for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy. *Applied Energy, **179***, 1395-1408. doi:10.1016/j.apenergy.2016.02.093

Poggi F, Firmino A, Amado M (2018) Planning renewable energy in rural areas: Impacts on occupation and land use. *Energy, **155***, 630-640. doi:10.1016/j.energy.2018.05.009

Saidur R, Rahim N, Islam M, Solangi K (2011) Environmental impact of wind energy. *Renewable and Sustainable Energy Reviews, **15***(5), 2423-2430.

Santangeli A, Toivonen T, Pouzols FM, Pogson M, Hastings A, Smith P, Moilanen A (2016) Global change synergies and trade-offs between renewable energy and biodiversity. *Global Change Biology Bioenergy, **8***(5), 941-951. doi:10.1111/gcbb.12299

Scheffers BR, De Meester L, Bridge TC *et al.* (2016) The broad footprint of climate change from genes to biomes to people. *Science, **354***(6313). doi:10.1126/science.aaf7671

Scholes RJ, Montanarella L, Brainich, E *et al.* (2018) *IPBES (2018): Summary for policymakers of the assessment report on land degradation and restoration of the Intergovernmental Science- Policy Platform on Biodiversity and Ecosystem Services*. Bonn, Germany: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.

Schuster E, Bulling L, Koppel J (2015) Consolidating the State of Knowledge: A Synoptical Review of Wind Energy's Wildlife Effects. *Environmental Management, **56***(2), 300-331. doi:10.1007/s00267-015-0501-5

Shum RY (2017) A comparison of land-use requirements in solar-based decarbonization scenarios. *Energy Policy, **109***, 460-462. doi:10.1016/j.enpol.2017.07.014

Smith RJ, Bennun L, Brooks TM *et al.* (2019) Synergies between the key biodiversity area and systematic conservation planning approaches. *Conservation Letters, **12***(1), e12625. doi:doi:10.1111/conl.12625

Söderman T (2006) Treatment of biodiversity issues in impact assessment of electricity power transmission lines: a Finnish case review. *Environmental impact assessment review, **26***(4), 319-338.

Sonter LJ, Herrera D, Barrett DJ, Galford GL, Moran CJ, Soares-Filho BS (2017a) Mining drives extensive deforestation in the Brazilian Amazon. *Nature Communications, **8***(1), 1013. doi:10.1038/s41467-017-00557-w

Sonter LJ, Johnson JA, Nicholson CC, Richardson LL, Watson KB, Ricketts TH (2017b) Multi-site interactions: Understanding the offsite impacts of land use change on the use and supply of ecosystem services. *Ecosystem services*, **23**, 158-164.

Sonter LJ, Ali SH, Watson JEM (2018) Mining and biodiversity: key issues and research needs in conservation science. *Proceedings of the Royal Society B*, **285**(1892), 20181926

Strantzali E, Aravossis, KJR (2016) Decision making in renewable energy investments: A review. *Renewable and Sustainable Energy Reviews,* ***55***, 885-898. doi:10.1016/j.rser.2015.11.021

Symes WS, Rao M, Mascia MB, Carrasco LR (2016) Why do we lose protected areas? Factors influencing protected area downgrading, downsizing and degazettement in the tropics and subtropics. *Global Change Biology*, **22**(2), 656-665. doi:10.1111/gcb.13089

Thaker M, Zambre A, Bhosale H (2018) Wind farms have cascading impacts on ecosystems across trophic levels. *Nature Ecology & Evolution,* ***2***(12), 1854-1858. doi:10.1038/s41559-018-0707-z

Thomas CD, Cameron A, Green RE *et al.* (2004) Extinction risk from climate change. *Nature,* ***427***, 145. doi:10.1038/nature02121

Trainor AM, McDonald RI, Fargione J (2016) Energy Sprawl Is the Largest Driver of Land Use Change in United States. *PLOS ONE,* ***11***(9), e0162269. doi:10.1371/journal.pone.0162269

Tucker MA, Böhning-Gaese K, Fagan WF *et al.* (2018) Moving in the Anthropocene: Global reductions in terrestrial mammalian movements. *Science,* ***359***(6374), 466-469. doi:10.1126/science.aam9712

UN (2015) Transforming our world: the 2030 Agenda for Sustainable Development. Retrieved from: https://sustainabledevelopment.un.org

UNCCD (2018) *Global Land Outlook, Chapter 10, Energy and Climate*. Retrieved from https://www.unccd.int

UNFCCC (2015) Adoption of the Paris agreement. *United Nations Office at Geneva, Geneva.* Retrieved from: https://unfccc.int/resource

Venter O, Sanderson EW, Magrach A *et al.* (2016) Sixteen years of change in the global terrestrial human footprint and implications for biodiversity conservation. *Nature,* ***7***, 12558. doi:10.1038/ncomms12558

Waite JL (2017). Land reuse in support of renewable energy development. *Land Use Policy,* ***66***, 105-110. doi:10.1016/j.landusepol.2017.04.030

Watson JEM, Dudley N, Segan DB, Hockings M (2014) The performance and potential of protected areas. *Nature*, **515**(7525), 67.

Watson JEM, Shanahan DF, Di Marco M *et al.* (2016) Catastrophic declines in wilderness areas undermine global environmental targets. *Current Biology,* **26**, 2929-2934. doi:10.1016/j.cub.2016.08.049

Watson JEM, Venter O (2017). A global plan for nature conservation. *Nature,* ***550***, 48. doi:10.1038/nature24144

Watson JEM, Evans T, Venter O, Williams B, Tulloch A, Stewart C, *et al.* (2018a) The exceptional value of intact forest ecosystems. *Nature ecology & evolution,* **2**(4), 599.

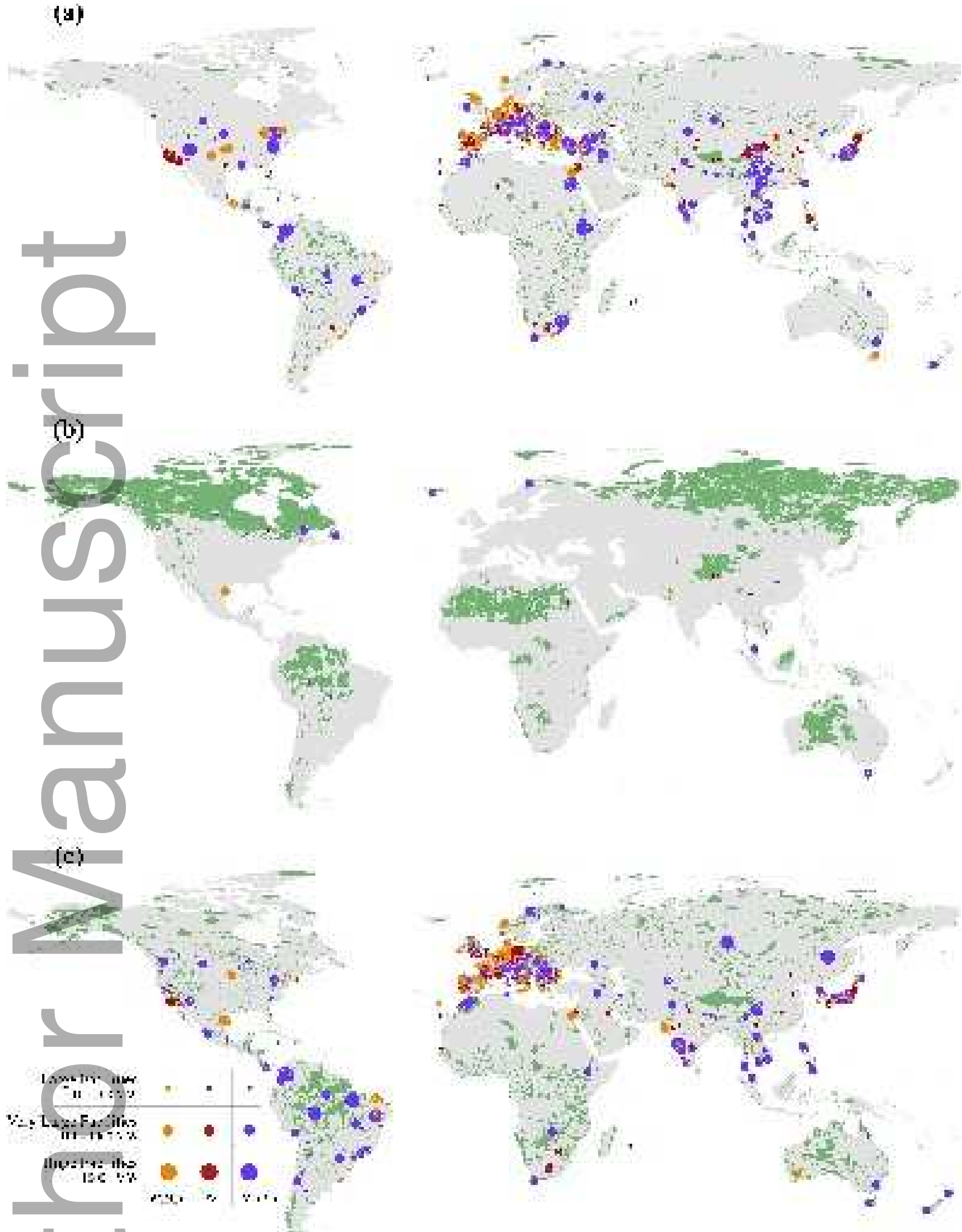
Watson JEM, Venter O, lee J, Jones KR, Robinson JG, Possingham HP, Allan JR (2018b) Protect the last of the wild. *Nature,* ***536***, 27 - 30.

Wu GC, Deshmukh R, Ndhlukula K, Radojicic T, Reilly J (2015) Renewable energy zones for the Africa clean energy corridor, multi-criteria analysis for planning renewable energy planning. IRENA. Retrieved from: https://www.irena.org/publications

Yackulic CB, Sanderson EW, Uriarte M (2011) Anthropogenic and environmental drivers of modern range loss in large mammals. *Proceedings of the National Academy of Sciences,* ***108***(10), 4024-4029. doi:10.1073/pnas.1015097108

Young PS, Cech JJ, Thompson LC (2011) Hydropower-related pulsed-flow impacts on stream fishes: a brief review, conceptual model, knowledge gaps, and research needs. *Reviews in Fish Biology and Fisheries,* ***21***(4), 713-731. doi:10.1007/s11160-011-9211-0

Zhou L, Tian Y, Roy SB, Thorncroft C, Bosart LF, Hu Y (2012) Impacts of wind farms on land surface temperature. *Nature Climate Change,* ***2***(7), 539. doi:10.1038/nclimate1505



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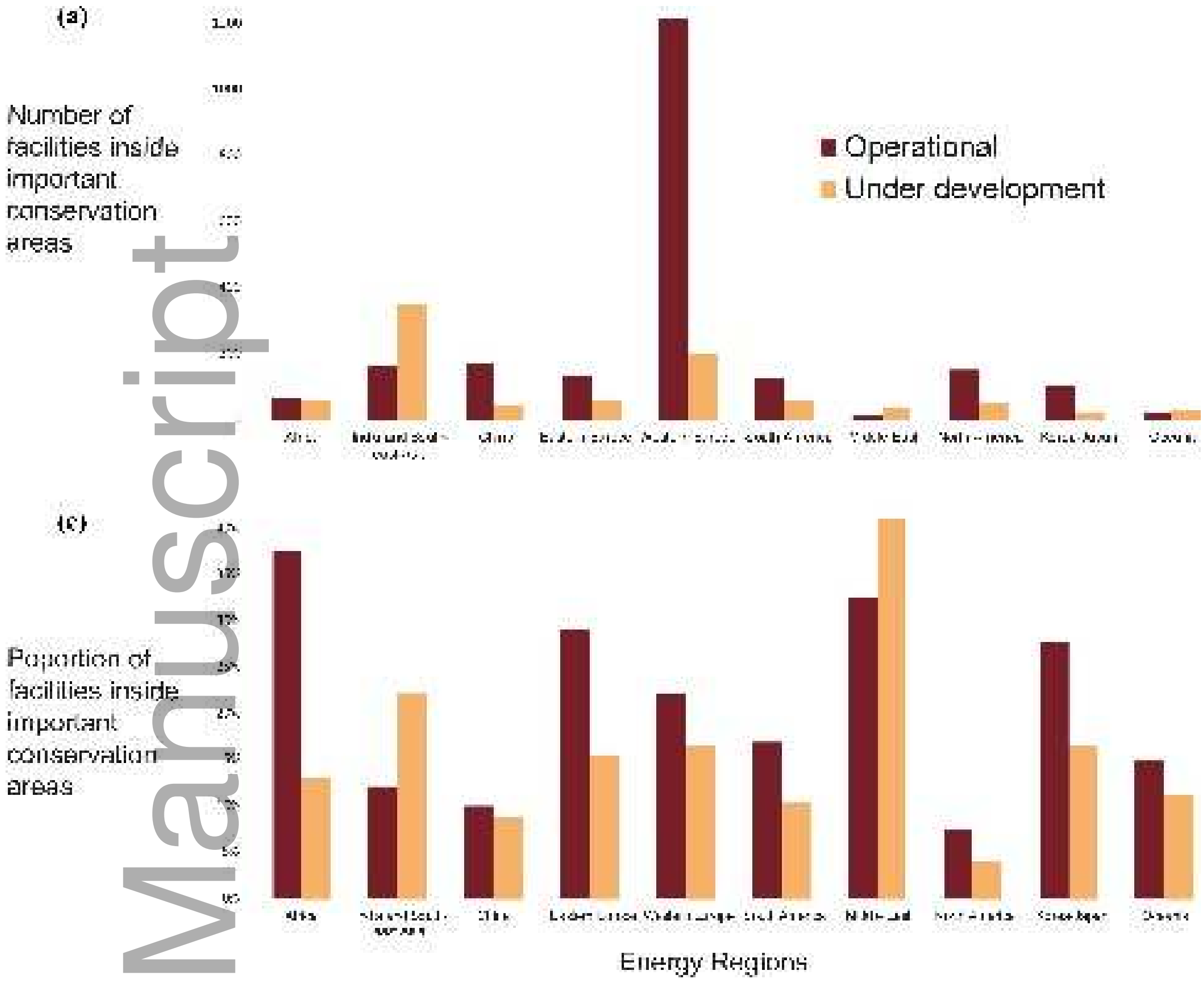

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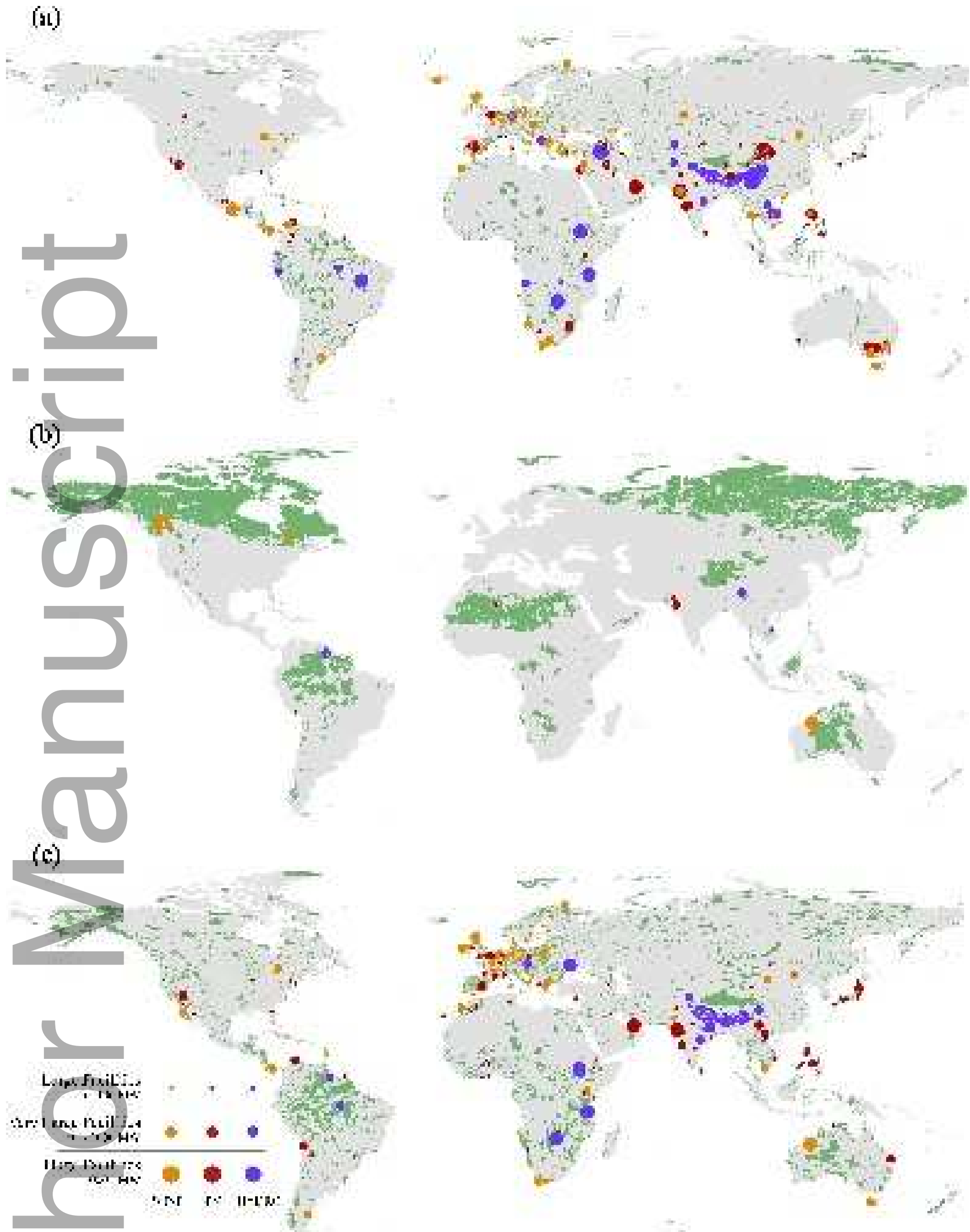

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